REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
06-30-2013	Final	04-01-2010 to 03-31-2013

4. TITLE AND SUBTITLE

Carbon-Based Avalanche Devices for Low-Power Electronics

5a. CONTRACT NUMBER

5b. GRANT NUMBER

FA9550-10-1-0082

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Illinois Urbana-Champaign

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Office of Science and Research
875 Randolph Street
Suite 325 Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution A-Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report summarizes our 3-year efforts in understanding operation and reliability of graphene transistors and interconnects supported by this AFOSR-YIP award. The core of the graduate student team has been Enrique Carrion (an underrepresented minority student), who has done excellent work and who will soon complete his PhD. Enrique has recently completed a study of top-gated graphene transistors, including their variability and other "real world" challenges. A junior student (Ning Wang) has been leading our work on carbon nanotubes (CNTs), including extensive modeling and fabrication of avalanche-induced switching in CNT transistors. More details can be found in the submitted PDF file, including all publications, conference proceedings, and invited talks supported in full or in part by this grant. Importantly, a major review paper on "Thermal Properties of Graphene: Fundamentals and Applications" was co-authored by the PI together with AFRL researchers A. Roy and V. Varshney, and published in MRS Bulletin, Dec 2012 issue. This collaboration with AFRL would not have been possible without this AFOSR-YIP grant. The PI also visited AFRL (WP-AFB) and hosted AFRL researchers at UIUC twice during the duration of this grant.

15. SUBJECT TERMS

graphene, contacts, variability, stress, thermal properties, high-field, velocity saturation

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Eric Pop, PI
U	U	U	UU	6	**19b. TELEPHONE NUMBER** *(include area code)* 217-244-2070

AFOSR-YIP 2010, Award **FA9550-10-1-0082**

Carbon-Based Avalanche Devices for Low-Power Electronics

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Period of Performance: 01-Apr-10 to 31-Mar-13

Final Report of Accomplishments

The third and final year of this AFOSR-YIP grant has seen the completion of projects begun in Years 1 and 2. The core of the graduate student team has been Enrique Carrion, who is doing excellent work and whose PhD thesis work is on track. Enrique has recently published a very interesting study of top-gated graphene transistors, including their variability and other "real world" challenges. Another student that joined us in Year 2 (Ning Wang) has been coming up to speed, under the leadership of Enrique. Ning has been leading our work on carbon nanotubes (CNTs), including extensive modeling and fabrication of avalanche-induced switching in CNT transistors.

Year 3: Our work in the final year has seen the completion and publication of a major review article co-authored by the PI (E. Pop) with two AFRL researchers (A. Roy and V. Varshney). The collaboration between Pop and the AFRL researchers would not have been possible without this grant, and it became an integral part of this project even though it could not have been foreseen when the grant was written! This review titled "Thermal Properties of Graphene: Fundamentals and Applications" was published in the *MRS Bulletin*, December 2012 issue and it has already garnered a substantial number of citations for the short time since its publication. Another study recently completed is that led by Enrique Carrion, titled "Nanosecond Pulsed Electrical Characterization of Top-Gated Graphene Transistors" and currently in revision at *IEEE Trans. Electron Devices*. This study examined the properties of graphene transistors from CVD-grown graphene, measured and modeled under realistic transport conditions, including their variability and imperfections. A related study (A. Behnam, *Nano Letters*, 2012) was the first to examine the properties of *nanoscale interconnects* from CVD-grown graphene nanoribbons (GNRs). In this work we found that the maximum current-carrying ability of such GNRs can be controlled by reducing their self-heating at high-field, and we have achieved current densities up 2×10^9 A/cm^2, almost as high as those of carbon nanotubes, even in spite of the GNR edge roughness. Finally, a

[1] In July 2013 (after the completion of this grant) the PI and his group moved to Stanford University, Electrical Engineering department. The new contact information is: e-mail epop@stanford.edu, tel: (650) 725-8768, web: http://poplab.stanford.edu and physical address: Stanford University, Allen Building, Room 335X, 420 Via Palou, Stanford, CA 94305.

collaboration supported in part by this AFOSR-YIP grant (E. Guerriero et al., *ACS Nano*, 2013) has led to the first demonstration of graphene circuits operating at speeds over 1 GHz. This has been a collaboration with the group of Prof. Roman Sordan at Politecnico di Milano in Italy, and has led to our group hosting a student from Italy, as well as very nice international collaboration experiences for the UIUC students involved.

Year 2: Here we briefly summarize the work reported last year, for the sake of completeness of this final report. Year 2 saw many advances building on Year 1 results (publication list attached). We completed three studies examining high-field transport and dissipation in graphene (Bae *et al*, ACS Nano 2011), graphene nanoribbons (Liao *et al*, Phys. Rev. Lett. 2011) and carbon nanotubes (Tsai *et al*, Appl. Phys. Lett. 2011). In particular, we found that thermal effects play a significant role in limiting the current density of graphene devices during high-field transport. We made our graphene simulation codes freely available to the community on the web site nanoHUB.org (as GFETTool). We have also carefully studied the effects of Cu substrate on graphene grown by chemical vapor deposition (CVD), and uncovered that Cu (111) surfaces yield the best monolayer graphene growth (Wood *et al*, Nano Lett. 2011). We continued our work making graphene nanoribbons (GNRs) from CVD-grown graphene, and the manuscript is now under revision (Behnam *et al*, Nano Lett. 2012). To our knowledge, this is the first time that GNRs have been fabricated and investigated on a large-scale vs. the single-device approaches presented in the past. Finally, we have implemented a pulsed measurement system to accurately measure carbon nanoelectronics with suppressed hysteresis and lower overall heating, which will be presented at the Device Research Conference in June 2012 (Carrion *et al*, DRC 2012).

A number of other publications and collaborations supported in part by this work have also appeared during the past year. These include thermal measurements of a "weakened" interface by a weakly-bonded graphene monolayer (Hsieh *et al*, PRB 2011), and two studies of the current-carrying ability of GNR interconnects (Wang, DRC 2012) and more broadly of GNRs and CNTs as 1-dimensional nanomaterials (Liao, APS 2012). These papers are listed in the list submitted online, and on the next two pages.

Year 1: To briefly summarize the work from Year 1 in this final report. In Year 1 we had developed a method for fabricating wafer-scale graphene nanoribbon transistors (GNRFETs) using graphene grown by chemical vapor deposition (CVD). We characterized the electrical properties of such devices and will present these results at the 2011 Device Research Conference. To our knowledge, this is the first time that large-scale GNRs have been fabricated and investigated vs. the single-device approaches presented by others in the past. We have also extended this fabrication process to make top gated GNRFETs; this work was presented at Graphene 2011 in Bilbao, Spain. In addition, we have developed a pulsed measurement system for accurately measuring the current of low-power carbon nanoelectronics with suppressed hysteresis and lower overall heating. These developments are summarized in the attached report.

A number of other publications and collaborations supported in part by this work have also appeared during Year 1. These include the first thermal measurements across (perpendicular) to graphene stacks from one to ten layers; the first report of thermoelectric effects at graphene transistor contacts; and the first measurements of the current carrying capability of GNRs, which was shown to be limited by self-heating. These papers are listed online, and on the next pages.

Publications Related to AFOSR-YIP10 award FA9550-10-1-0082

Those that represent work completed during the final Year 3 are **highlighted in bold**:

Journal Publications:

1) K.L. Grosse, M.-H. Bae, F. Lian, E. Pop, W.P. King, "Nanoscale Joule heating, Peltier cooling and current crowding at graphene-metal contacts," *Nature Nanotechnology* 6, 287 (2011)

2) Y.K. Koh, M.-H. Bae, D.G. Cahill, E. Pop, "Reliably Counting Atomic Planes of Few-Layer Graphene (n>4)," *ACS Nano* 5, 269 (2011)

3) M.-H. Bae, Z.-Y. Ong, D. Estrada, E. Pop, "Imaging, Simulation, and Electrostatic Control of Power Dissipation in Graphene Devices," *Nano Letters* 10, 4787 (2010) [cover article]

4) A. Liao, J. Wu, X. Wang, K. Tahy, D. Jena, H. Dai, E. Pop, "Thermally-Limited Current Carrying Ability of Graphene Nanoribbons," *Phys. Rev. Letters* 106, 256801 (2011)

5) C.-L. Tsai, A. Liao, E. Pop, M. Shim, "Electrical Power Dissipation in Semiconducting Carbon Nanotubes on Single Crystal Quartz and Amorphous SiO_2," *Appl. Phys. Lett*. 99, 053120 (2011)

6) M.-H. Bae, S. Islam, V.E. Dorgan, E. Pop, "Scaling of High-Field Transport and Localized Heating in Graphene Transistors," *ACS Nano* 5, 7936 (2011)

7) J.D. Wood, S.W. Schmucker, A.S. Lyons, E. Pop, J.W. Lyding, "Effects of Polycrystalline Cu Substrate on Graphene Growth by Chemical Vapor Deposition," *Nano Letters* 11, 4547 (2011) – top 10 most downloaded articles in month of Nov 2011.

8) W.-P. Hsieh, A.S. Lyons, E. Pop, P. Keblinski, D.G. Cahill, "Pressure Tuning of the Thermal Conductance of Weak Interfaces," *Phys. Rev. B* 84, 184107 (2011)

9) A. Behnam, A.S. Lyons, M.-H. Bae, E.K. Chow, S. Islam, C.M. Neumann, E. Pop, "Transport in Nanoribbon Interconnects Obtained from CVD-Grown Graphene," *Nano Letters* 12, 4424 (2012).

10) E. Pop, V. Varshney, A.K. Roy, "Thermal Properties of Graphene: Fundamentals and Applications," [Invited Review] *MRS Bulletin* 37, 1273 (2012)[2]

[2] Co-authored with two AFRL researchers, Dr. Vikas Varshney and Dr. Ajit Roy.

11) Y. An, A. Behnam, E. Pop, A. Ural, "Metal-Semiconductor-Metal Photodetectors Based on Graphene/p-type Silicon Schottky Junctions," *Appl. Phys. Lett.* 102, 013110 (2013)

12) E. Guerriero, L. Polloni, M. Bianchi, A. Behnam, E.A. Carrion, L.G. Rizzi, E. Pop, R. Sordan, "Gigahertz Integrated Graphene Ring Oscillators," *ACS Nano* 7, 5588-5594 (2013)

13) M.P. Gupta, A. Behnam, F. Lian, D. Estrada, E. Pop, S. Kumar, "High Field Characteristics of Carbon Nanotube Thin Film Transistors," *Nanotechnology*, in press (2013)

14) E.A. Carrion, A. Malik, A. Behnam, S. Islam, A.Y. Serov, F. Xiong, M. Bianchi, R. Sordan, E. Pop, "Nanosecond Pulsed Electrical Characterization of Top-Gated Graphene Transistors," *IEEE Trans. Electron Devices*, in revision (2013).

Conference Publications (refereed):

1) A.S. Lyons, A. Behnam, E.K. Chow, E. Pop, "Transport Properties of CVD-Grown Graphene Nanoribbon Field-Effect Transistors," *Device Research Conference (DRC)*, June 2011, Santa Barbara CA

2) A. Liao, J. Wu, X. Wang, K. Tahy, D. Jena, H. Dai, E. Pop, "Thermally-Limited Current Carrying Ability of Graphene Nanoribbons," *Graphene 2011*, Apr 2011, Bilbao, Spain

3) A.S. Lyons, E.K. Chow, V.E. Dorgan, E. Pop, "Large Scale CVD Graphene Nanoribbon Transistors with High-κ Dielectrics and Top Gates," *Graphene 2011*, Apr 2011, Bilbao, Spain

4) S. Islam, M.-H. Bae, V. Dorgan, E. Pop, "Effect of Oxide Thickness Scaling on Self-Heating in Graphene Transistors," *IEEE Device Research Conference (DRC)*, Jun 2011, Santa Barbara CA

5) A. Behnam, A. Lyons, M.-H. Bae, E.K. Chow, S. Islam, C.M. Neumann, E. Pop, "Graphene Nanoribbons from CVD Graphene," *MRS Spring Meeting*, Apr 2012, San Francisco CA

6) A.D. Liao, C. Neumann, E. Pop, "Fundamental Limits of Current Flow in One-dimensional Carbon Nanomaterials," *APS March Meeting*, Mar 2012, Boston MA

7) E. Carrion, A. Malik, A. Behnam, S. Islam, F. Xiong, E. Pop, "Pulsed Nanosecond Characterization of Graphene Transistors," *IEEE Device Research Conference (DRC)*, Jun 2012, State College PA

8) N. Wang, C.D. English, E. Pop, "Comparison of Graphene Nanoribbons With Cu and Al Interconnects," *IEEE Device Research Conference (DRC)*, Jun 2012, State College PA

9) Z. Li, M.-H. Bae, P. Martin, E. Pop, "Ballistic to Diffusive Crossover of Phonon Flow in Graphene Ribbons," *Phonons 2012*, Jul 2012, Ann Arbor, MI

10) J.D. Wood, S.W. Schmucker, R.T. Haasch, G.P. Doidge, L. Nienhaus, G.L. Damhorst, A.S. Lyons, M. Gruebele, R. Bashir, E. Pop, J.W. Lyding, "Improved Graphene Growth

and Fluorination on Cu with Clean Transfer to Surfaces," *IEEE Nano,* Aug 2012, Birmingham UK

11) A.D. Liao, C.M. Neumann, E. Pop, "Probing the Upper Limits of Current Density in One-Dimensional Carbon Interconnects," *MRS Fall Meeting,* Nov 2012, Boston MA

12) V.E. Dorgan, A. Behnam, E. Pop, "High-Field Transport in Suspended Graphene," *MRS Spring Meeting,* Apr 2013, San Francisco CA

13) S. Islam, A.Y. Serov, I. Meric, K.L. Shepard, E. Pop, "Substrate Dependent High-Field Transport of Graphene Transistors," *IEEE Device Research Conference (DRC),* Jun 2013, Notre Dame IN

14) A.Y. Serov, S. Islam, E. Pop, "Realistic Simulation of Graphene Transistors Including Non-Ideal Electrostatics," *IEEE Device Research Conference (DRC),* Jun 2013, Notre Dame IN

15) E.A. Carrion, M. Tung, A. Malik, A. Behnam, E. Pop, "Variability of Graphene Transistors: Roles of Contacts and Enhanced Characterization Techniques," *SRC TECHCON,* Sep 2013, Austin TX

16) A.Y. Serov, S. Islam and E. Pop, "Simulation of realistic graphene transistors including non-ideal behavior," *SRC TECHCON,* Sep 2013, Austin TX

17) S. Islam, A.Y. Serov, E. Carrion, E. Pop, "Effect of Channel Length Scaling on Current Saturation in Graphene Transistors," *SRC TECHCON,* Sep 2013, Austin TX

18) V.E. Dorgan, A. Behnam, H.J. Conley, K.I. Bolotin, E. Pop, "High-Field Electrical and Thermal Transport in Suspended Graphene," *SRC TECHCON,* Sep 2013, Austin TX

Invited Talks Given by the PI: (**Year 3 of grant only**)

1. IWCE (Intl. Workshop Computational Electronics), Nara, Japan, Jun 2013
2. Keio University EE Seminar, Tokyo, Japan, Jun 2013
3. Univ. Tokyo ME Seminar, Tokyo, Japan, Jun 2013
4. HGST (Hitachi Global Storage Technologies) seminar, San Jose CA, May 2013
5. Stanford Energy & Environment Affiliates Program (EEAP), Stanford CA, May 2013
6. UT Austin, Nanoscale Thermal Energy Symposium, Austin TX, May 2013
7. Intel Corp., memory seminar, Santa Clara CA, Apr 2013
8. MRS Spring Meeting, San Francisco CA, Apr 2013
9. Univ. Minnesota, Mechanical Engineering Colloquium, Minneapolis MN, Mar 2013
10. Beckman Institute Director's Seminar, Univ. Illinois Urbana-Champaign, Urbana IL, Jan 2013
11. MRS Fall Meeting, Boston MA, Nov 2012
12. IEEE Nanotechnology Materials and Devices Conf. (IEEE-NMDC), Honolulu HI, Oct 2012

13. Wright-Patterson Air Force Research Labs (AFRL), Dayton OH, Oct 2012
14. Intl. Materials Research Congress (MRS-IMRC), Cancun Mexico, Aug 2012
15. CMOS Emerging Technologies (ET) Conference, Vancouver BC, Canada, Jul 2012
16. Silicon Nanoelectronics Workshop (IEEE-SNW), Honolulu HI, June 2012
17. IEEE Intl. Conference on IC Design and Technology (IEEE-ICICDT), Austin TX, May 2012
18. UT Dallas, Materials Science & Engineering Seminar, Dallas TX, May 2012
19. U. Washington, Center for Nanotechnology Seminar, Seattle WA, Apr 2012
20. MRS Spring Meeting, San Francisco CA, Apr 2012
21. MIT, EECS Seminar, Cambridge MA, Apr 2012
22. Georgia Tech, MRSEC Seminar Series, Atlanta GA, Mar 2012